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METHOD TO IMPROVE THE PERFORMANCE OF FIBER TRANSMISSION SYSTEMS BY TRANSFORMING RETURN-TO-ZERO FORMAT TO NON-RETURN-TO-ZERO FORMAT IN FRONT OF RECEIVER

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References Cited

U.S. PATENT DOCUMENTS

HP 0,007,216 A1 9/2002 Chraplyvy et al. 359/161

HP 6,448,913 B1 10/2002 Prucnal et al. 341/137

HP 6,243181 B1 5/2001 Golovchenko et al. 359/161

HP 6,163,394 12/2000 Webb et al. 359/181

Other Publications

HP G. P. Agrawal, *Fiber Optic Communication Systems*, John Wiley & Sons, 1997, pp. 157, 172.

HP G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, 1995, pp. 102-111.

HP J. P. Gordon, H. A. Haus, "Random walk of coherently amplified solitons in optical fibers", Opt. Lett., Vol. 11, Oct., 1986, pp.665-667.

10/26/04 J. P. Gordon, "Interaction forces among solitons in optical fibers", Opt. Lett., Vol. 8, Nov. 1983, pp.596-598.

Bakshi et al, "Soliton interaction penalty reduction by receiver filtering", *IEEE Photon. Tech. Lett.*, Vol. 10, 1998, pp. 1042-1044.

A. Hasegawa, & Y. Kodama, *Solitons in optical Communications*, Claredon Press, Oxford, 1995.

M. Suzuki, H. Toda, A. Liang, & A. Hasegawa "Experimental Verification of Improvement of a phase margin in optical RZ receiver using Kerr nonlinearity in normal dispersion fibers", ECOC'00, Munich, Germany, vol. 4, 2000, pp. 49-50.

M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250.

M. Suzuki and H. Toda, "Q-factor improvement in a jitter limited optical RZ system using nonlinearity of normal dispersion fiber placed at receiver", OFC'2001, Anaheim, 2001, paper WH3.

L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310.

S. Park et al, "Chirp consequences of all-optical RZ to NRZ conversion using cross-phase modulation in an active semiconductor photonic integrated circuit", IEEE Photonics Technol. Lett., Vol. 12, N. 3, 2000, pp. 233-235.

Y. Kodama et al, "Compensation of NRZ signal distortion by initial frequency frequency shifting", Electron. Lett., vol. 31, 1995, pp.1761-172.

T. Naito et al, "Four 5-Gbit/s WDM transmission over 4760 km straight-line using pre- and post-dispersion compensation and FWM cross talk reduction", In Conf. Optical Fiber Communications'96, Washington D. C., 1996, paper WM3.

T. Georges, "Transmission systems based on dispersion-managed solitons: theory and experiment", in *New Trends in Optical Soliton Transmission Systems*, Ed. By A. Hasegawa., Kluwer Academic Publishers, 1997, pp. 317-340.

N. Bergano, et al, " 640 Gb/s transmission of sixty-four 10 Gb/s WDM channels over 7200 km with 0.33 (bits/s)/Hz spectral efficiency", OFC'99, 21-26 Feb., 1999, paper PD2.

K. Tai, A. Hasegawa, and A. Tomita, Phys. Rev. Lett., vol. 56, 1986, pp. 135-137.

M. Suzuki, et al., "Reduction of Gordon Haus timing jitter by periodic dispersion compensation in soliton transmission", Electron. Lett., vol. 31, 1995, pp. 2027-2029.

N. J. Doran et al., "Remarkable Feature of DM Solitons: Implications for high speed and WDM systems", in *New Trends in Optical Soliton Transmission Systems*, Ed. By A. Hasegawa., Kluwer Academic Publishers, 1997, pp. 303-316.

CROSS-REFERENCE TO RELATED APPLICATIONS

Not applicable.

STATEMENT REGARDING FEDERALLY SPONSORSED ~~RESEARCH~~ OR DEVELOPMENT

Not applicable.

REFERENCE TO A MICROFICHE APPENDIX

Not applicable.

BACKGROUND OF THE INVENTION

The present invention relates to the transformation of high speed (i.e. 10, 40 Gbit/s or higher bit rate) Return to Zero (RZ) pulses to Non-Return to Zero (NRZ) pulses in front of the optical receiver in optical fiber communication systems with the purpose of increasing the tolerances of the generalized timing-jitter and the amplitude fluctuation.

In present optical fiber communication systems, one normally uses optical amplifiers (i.e. Erbium-doped-fiber-amplifier (EDFA) or/and Raman amplifiers) as repeaters to compensate the fiber loss. The accumulated amplified spontaneous emission

(ASE) noise generated by EDFA or/and Raman amplifiers induces the degradation of optical signal to noise ratio (OSNR) and increases amplitude fluctuation. In front of the receiver, a band-pass optical filter is normally used to filter out the ASE, and the optical signal is converted to the electrical signal by a photodetector (e.g. PIN or APD) in the receiver. After the photodetector, the electrical signal is amplified by a high gain amplifier and then it is filtered by an electrical Bessel-Thompson low-pass filter which is used to reduce the electrical noise (See G. P. Agrawal, *Fiber Optic Communication Systems*, John Wiley & Sons, 1997, pp. 157). The low-pass filter shapes the voltage pulse. One main purpose is to reduce the noise without introducing much intersymbol interference (ISI). After passing the low pass filter, the electrical pulse spreads beyond the allocated bit slot. Such a spreading can interfere with the detection of neighboring bits, a phenomenon referred to as ISI. In addition to reduce the noise, the electrical Bessel-Thompson low-pass filter can also reduce the influence of the generalized timing jitter which means the pulse position randomly changes because of the noise and some other effects. The generalized timing jitter includes the Gordon-Haus timing jitter, and the pulse position variation induced by the pulse interaction, interchannel cross talk (including cross-phase modulation and four-wave-mixing), and polarization-mode-dispersion (PMD) etc. The Gordon-Haus timing jitter originates from the noise induced random nonlinear frequency shift when the fiber dispersion is not zero (See J. P. Gordon, H. A. Haus, "Random walk of coherently amplified solitons in optical fibers", Opt. Lett., Vol. 11, Oct., 1986, pp.665-667.); the nonlinear pulse interaction between two neighboring pulses also induces the generalized timing jitter (See. J. P. Gordon, "Interaction forces among solitons in optical fibers", Opt. Lett., Vol. 8, Nov. 1983, pp.596-598.); The cross-phase modulation between different channels of wavelength-division-multiplexing (WDM) also induces the generalized timing jitter; PMD, which means the difference in group velocity for two orthogonal polarized modes, also induces the pulse position shift and ISI.

Displacement of pulse position at receiver caused by the generalized timing jitter causes the bit error. The Bessel-Thompson low pass filter can broaden the pulse width and reduce the influence of the generalized timing jitter of received pulses (See B. Bakshi, et al, "Soliton interaction penalty reduction by receiver filtering," *IEEE Photon.*

Tech. Lett., vol. 10, 1998, pp. 1042-1044.). A narrower bandwidth of the low pass filter results in lesser noise and lesser serious influence of the generalized timing jitter. However it worsens the ISI and lower signal amplitudes. A broader low pass filter results in better ISI and higher signal amplitudes. However, it induces more noise and more serious influence of the generalized timing jitter. The way to chose 3 dB bandwidth of the low pass filter is an art to get a trade off between the noise, the generalized timing jitter, sensitivity and ISI. Typically, one chooses the 3 dB bandwidth of low pass filter Δf=0.5-0.8 bit rate for both RZ and NRZ pulses (See Bakshi et al, "Soliton interaction penalty reduction by receiver filtering", *IEEE Photon. Tech. Lett.*, vol. 10, 1998, pp. 1042-1044.).

This low pass filter technique is widely used in RZ optical communication systems. In here, RZ pulses include but not limited to the conventional soliton, dispersion managed (DM) soliton, non-chirped RZ, chirped RZ (CRZ), carrier-suppressed RZ (CS-RZ), carrier-suppressed chirped RZ (CS-CRZ) and differential phase-shift-keyed (DPSK) formats. The conventional soliton takes advantage of fiber nonlinearity to compensate for fiber dispersion in optical fiber systems with rough constant dispersion (A. Hasegawa, & Y. Kodama, Solitons in Optical Communications, Claredon Press, Oxford, 1995); and the DM soliton takes advantage of fiber nonlinearity to compensate the average dispersion of fiber link consisted of positive and negative dispersion fibers; non-chirped RZ means that the RZ pulses without frequency chirping; CRZ means RZ pulses with frequency chirping; CS-RZ means the nearby non-chirped RZ pulses with opposite phase; CS-CRZ means the nearby chirped RZ pulses with opposite phase. Among these various formats of RZ pulses, all of the pulses have non-flat-top bell-like shape (e.g. Gaussian, hyperbolic sech, and the shape between them etc.). In these systems, pre-compensation at transmitter, inline dispersion compensation in the transmission link and post compensation at receiver may be used (See Y. Kodama et al, "Compensation of NRZ signal distortion by initial frequency frequency shifting", Electron. Lett., vol. 31, 1995, pp.1761-172; T. Naito et al, "Four 5-Gbit/s WDM transmission over 4760 km straight-line using pre- and post-dispersion compensation and FWM cross talk reduction", In Conf. Optical Fiber Communications'96, Washington D. C., 1996, paper WM3; T. Georges, "Transmission systems based on

dispersion-managed solitons: theory and experiment", in New Trends in Optical Soliton Transmission Systems, Ed. By A. Hasegawa., Kluwer Academic Publishers, 1997, pp. 317-340; N. Bergano, et al, " 640 Gb/s transmission of sixty-four 10 Gb/s WDM channels over 7200 km with 0.33 (bits/s)/Hz spectral efficiency", OFC'99, 21-26 Feb., 1999, paper PD2; A. Chraplyvy et al., "Long haul transmission in a dispersion managed optical communication system", Jan. , 20003, US 2003/0007216 A1).

In high speed (e.g., the bit rate of per channel is 10 Gbit/s, 40 Gbit/s or even higher) optical transmission systems, normally RZ format has better transmission performance than NRZ format. However, with respect to detection at receiver, the NRZ format has better generalized timing jitter tolerance than the RZ format. To illustrate the reason simply, we assume that there are no ISI and noises for both ONE and ZERO rails and there is not the low pass filter at first, and the optimum decision threshold is about 0.5. When the RZ pulse format is used, the detection time is chosen at the average peak which is obtained by averaging millions of bits. The detected voltage of each RZ pulse at the specific detection time decreases if the pulse peak shifts from its average peak position because of the generalized timing jitter. When the detected voltage gets less than the optimum decision threshold 0.5, i.e. when the displacement of pulse peak position from the generalized timing jitter is larger than the half of the full-width-half-maximum (FWHM) pulse width, the bit error occurs. Similarly, for NRZ format, when the displacement of the center of pulse position is larger than the half of FWHM pulse width, which is half of the bit period (e.g. 50 ps for a 10 Gbit/s channel), the bit error occurs. The FWHM pulse width of NRZ pulses is broader than that of RZ pulses, so the NRZ format has larger generalized timing jitter tolerance than the RZ format at the receiver. Although the low pass Bessel-Thompson filter are normally added after the photodetector to broaden the pulse width and thence to reduce the influence of the generalized timing jitter, the technique also induces the ISI. Therefore, it is better to use RZ as the transmission format and NRZ as the detection format for a better system performance (see M. Suzuki, H. Toda, A. Liang, & A. Hasegawa "Experimental Verification of Improvement of a phase margin in optical RZ receiver using Kerr nonlinearity in normal dispersion fibers," ECOC'00, Munich, Germany, vol. 4, pp. 49-50, 2000.). In all of existing systems, the same format (either NRZ or RZ) is used for both

transmission and detection. In this invention, we first propose to insert an optical pulse transformer, which use the high Kerr nonlinear effect for very high power pulses in normal dispersion fibers to transform the transmitted RZ pulses (i.e. the transmission format) to NRZ pulses (i.e. the detection format), in front of the photodetector. This invention improves the performance of high speed (i.e. 10, 40 Gbit/s or higher) RZ transmission systems. This invention reduces the influence of the generalized timing jitter without increasing the ISI. Furthermore, the technique also reduces the amplitude fluctuation significantly. The bit-error-rate (BER), which is defined as the probability of incorrect identification of a bit by the decision circuit of the receiver, is normally used to judge the performance of a transmission system. The lower the BER, the better the performance. Equivalently, one also often uses the Q factor for the system perforemance, where the Q relates to the BER by (See G. P. Agrawal, *Fiber Optic Communication Systems*, John Wiley & Sons, 1997, pp. 172)

$$BER = \frac{1}{\sqrt{\pi}} \int_{\frac{Q}{\sqrt{2}}}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx \qquad (1)$$

The higher the Q factor, the lower the BER, the better the system performance. In long haul and metro optical fiber systems, it is very important to improve the Q factor (i.e. to reduce the BER).

US Pat. No. 6,448,913 B1 issued to Prucnal et al. discloses a RZ to NRZ optical pulse transformer (i.e. data format converter) based on Terahertz Optical Asymmetric Demultiplexer (TOAD), however, Pruncnal et al's patent differs fundamentally from this invention in following aspects:

1. Prucnal et al's patent for transferring RZ to NRZ degrades the system performance seriously instead of improving it, while the present invention improves the Q (i.e. system performance) by at least 5.4 dB , .The experimental results described in the paper written by Prucnal et al shows that their technique has at least 7 dB of Q penalty or 12 dB of power penalty (see Fig. 5 of L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310.). Contrary to their result, our experiment using the present

invention demonstrates an increase of the Q factor by 5.4 dB, which is a significant improvement on system performance (see M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250.).

2. Pruncnal et al's patent is not suitable for the data transformer application just in front of receiver, because their invention degrades the performance instead of improving the performance (however, their patent may be useful in other applications, e.g. wavelength conversion), but our optical pulse transformer is useful for the application in front of receiver.

3. Although they claim their patent is a RZ to NRZ pulse transformer, their original patent is actually only for RZ pulse broadening, and the RZ pulse does not change to NRZ pulse or even rectangular or flat-top pulse at all as can be seen from Fig. 3 in their patent (see Prucnal et al., Sept., 2002, US Pat. No. 6,448,913 B1) and Fig. 2 in their paper (see L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310.). In their experiments, their so called "NRZ pulse" is really RZ pulse with very low duty ratio. They need to use the pulse duplicator to duplicate the RZ pulse at first to get the real NRZ pulses (as shown in their paper in 2003), but they did not have the duplicator in their granted patent in 2001.

4. Even with a pulse duplicator, the generated NRZ pulses in their experiment have much larger amplitude ripples than those of our invention (compare Fig. 4 (b) of L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310, to Fig. 4 of M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250 .). In the present invention, the amplitude fluctuation of the generated NRZ pulses is very small and even smaller than

the input bell shape RZ pulses, because of the nonlinear effect (the nonlinear clamping), which is induced from the high self-phase modulation in the normal dispersion fibers.

5. Their patent is inappropriate for high bit rate pulses because of slow carrier recovery time of semiconductor optical amplifier (SOA) (around 180- 250 ps typically). In their format conversion patent, there is a trade off for the SOA carrier recovery time, which should be long enough to get a flat top on the converted NRZ pulses and short enough to reduce pattern-dependent effects and to get sharp rising and falling edges on the converted pulses (see Fig. 4 (b) of L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310.). Therefore their schemes on format conversion are good only for 1-5 Gbit/s, no 10 Gbit/s or higher bit rate converters have been demonstrated . On the contrary, the present invention works well for 10, 40 Gbit/s and higher bit rate format conversion; we have demonstrated the 10 Gbit/s format conversion.

6. The optical pulse transformer in their invention is more complex and expensive than that in our invention.

7. The optical pulse transformer in their invention can not be used for multiple wavelengths because of the cross gain modulation of SOAs; the cross gain modulation is one of the main obstacles to use SOAs in WDM/DWDM systems. The optical pulse transformer in present invention can be used for multiple wavelengths at the same time as long as the channel spacing is large enough. Therefore, it will further reduce our cost significantly.

Although the NRZ format is good at receiver to reduce the influence of the generalized timing jitters, the ISI, which may be induced by the pattern-dependant effects or the pulse broadening effect induced by PMD, may be large in some systems. In particular in a system without too large timing jitter, it will be helpful to use the quasi-NRZ format instead of the strict NRZ format. Here the quasi-NRZ pulses are with flat top (i.e. rectangular) shape and there are gap between neighbor pulses and the duty ratio can be in a range of 1:3 to 1:1 instead of 1:1 for strict NRZ pulses. In the present invention, the optical pulse transformer can convert a bell shape RZ pulse to either a strict NRZ or a quasi-NRZ pulse. The gap between the flat-top quasi-NRZ pulses can act as a guard band

to avoid the ISI induced from PMD which tends to broaden the pulses, in this case, our pulse transformer acts as a PMD compensator also. Our experiments demonstrated that our pulse transformer from RZ to quasi-NRZ works well even after a 16,000 km of transmission link where the transmitted pulses experience a lot of timing jitter and PMD (see M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250).

In our optical pulse transformer, the transmitted RZ pulses are first amplified by an optical amplifier then launched into the normal dispersion fibers. The launched RZ pulses have very high power, which can be equivalent to the power of many higher order solitons (i.e. N>>1) in normal dispersion region, where N^2, which equals Dispersion Length/Nonlinear Length, increases with power and decreases with dispersion of fiber. The launched high power bell shape RZ pulses as they propagate along the normal dispersion fibers with Kerr effect, their temporal waveforms change to a rectangular or flat top pulses (i.e. quasi- NRZ pulses) with steep leading and trailing edges (See G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, pp. 102-111, 1995). In our experiment, the launched RZ pulses have as high as 10-13th of equivalent soliton order in a normal dispersion fiber. Our experiment demonstrated that the optical pulse transformer not only increases the generalized timing jitter tolerance but also reduces the amplitude fluctuation and the ISI influence, so it enables us to have larger phase and amplitude margins (see M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250.). As shown in Fig. 9, our experiment shows that the amplitude fluctuations, which mainly comes from the pulse interactions and ASE noise, of converted flat-top quasi-NRZ pulses are pretty small and are even smaller than the original amplitude fluctuations of transmitted RZ pulses, we identify this phenomena as the nonlinearity clamping that occurs in normal dispersion region for pulses having a large power (See K. Tai, A. Hasegawa, and A. Tomita, Phys. Rev. Lett., vol. 56, 1986, pp. 135-137.). We note that the role, mechanics and locations for the normal dispersion fiber in our optical pulse transformer differs from those in dispersion managed RZ and NRZ systems. In dispersion

managed RZ and NRZ systems (e.g. dispersion managed soliton, CRZ, CS-RZ systems etc.), the normal dispersion fibers, which are used in each span or several spans of a transmission link, are used as in line dispersion compensators to compensate for the anomalous dispersion of transmission fibers and reduce the timing jitter and amplitude jitter influence induced from four-wav-mixing and cross-phase modulations (See Golovchenko et al, US Patent 6,243181 B1; M. Suzuki, et al., "Reduction of Gordon Haus timing jitter by periodic dispersion compensation in soliton transmission", Electron. Lett., vol. 31, 1995, pp. 2027-2029; N. J. Doran et al., "Remarkable Feature of DM Solitons: Implications for high speed and WDM systems", in *New Trends in Optical Soliton Transmission Systems*, Ed. By A. Hasegawa., Kluwer Academic Publishers, 1997, pp. 303-316.). In all these dispersion managed systems, the nonlinear effect in the normal fibers is always week (i.e. the equivalent soliton order N is always less than one and is typically much less than one because relative low optical power), and the linear dispersion effect is the dominant effect. However in the normal dispersion fiber of our optical pulse transformer, the nonlinear effect is dominant and is very strong (i.e. the equivalent soliton order N is much larger than one because of very high optical power), and the linear dispersion effect only plays a minor role. For example, in our experiment, the equivalent soliton order is as high as 10-13 th for the launched high power pulses. The normal dispersion fibers of our optical pulse transformer are located after the transmission link, which can be a dispersion managed link, but not in the transmission link as in line dispersion compensation fibers like those in other people's dispersion managed systems. After RZ pulses transmitting over their dispersion managed link, there are normally still a lot of amplitude and timing jitters left, so our pulse transformer can be used to further reduce the left amplitude and timing jitters and improve the Q further. In some transmission systems, where the normal dispersion fibers are used as the post dispersion compensation, primarily the linear dispersion effect, instead of the nonlinear effect, is used. The linear dispersion effect in our pulse transformer only plays very little role to compensate the residual dispersion of the whole transmission link, and the nonlinear effect plays major role in reducing the influences of timing jitters and amplitude jitter. For example, in our experiment for the 10 Gbit/s soliton transmission, the dispersion and length for transmission fibers are 0.88 ps/km/nm and 12,000 km

respectively, and the dispersion and length for the normal dispersion fiber in the transformer are -3 ps/km/nm and 20 km respectively. (see M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250). The total dispersion of normal dispersion fiber in the transformer only compensates the total residual dispersion by about 0.6% (i..e. 60 over 10560 ps/nm).

SUMMARY OF THE INVENTION

The object of the present invention is to improve system performance (i.e. Q) of high bit rate (i.e. 10, 40 Gbit/s and upper) fiber transmission systems whereby the non-flat-top bell shape RZ pulses are used in the transmitter as the transmission format, transmitting the RZ pulses over long distance of transmission link, then transforming the RZ format to the flat-top NRZ pulses or quasi-NRZ pulses by an optical pulse transformer which takes advantage of strong nonlinear effect for high power pulses in normal dispersion fibers, then finally detecting the NRZ or quasi-NRZ format by the receiver. Here the quasi-NRZ pulses are flat top or rectangular pulses with a duty ratio of 1:3-1:1. The RZ to NRZ pulse transformer consists of at least one optical amplifier (e.g. EDFA or Raman amplifier) and a fiber with normal dispersion, where the transmitted RZ pulses are amplified by the amplifier to a power level of equivalent of many higher order solitons (i.e. N>3 with N the equivalent soliton order), then the high power RZ pulses are launched into the normal dispersion fiber. In the normal dispersion fiber with Kerr effect, the high power RZ pulses change to flat-top or rectangular-like pulses with steep leading and trailing edges (See G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, pp. 102-111, 1995). The optical pulse transformer can not only increase the generalized timing jitter tolerance but also reduce the amplitude fluctuation and the ISI influence, so it provides larger amplitude and phase margins (See M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250.). In the optical pulse transformer, the nonlinear shaping effect, which transforms RZ pulses to flat top pulses by Kerr nonlinear effect, plays an

important role to improve the system performance as well as the nonlinear clamping (which decrease the amplitude fluctuations by the nonlinearity in normal dispersion region) does. After the optical amplifier in the optical pulse transformer, there may be an optical filter to filter the ASE depending on whether the accumulated ASE in the transmission link has been filtered out or not prior to the optical pulse transformer. The transformer can be used as a single channel as well as multiple channels pulse transformer. In multiple channel transformer case, however, because the optical spectrum of converted NRZ pulses have been broadened seriously by the high nonlinear effect, the channel spacing in transformer should be chosen wide enough to avoid FWM and cross-phase modulation. The channel spacing (e.g. 400 GHz) in the transformer is normally larger than that (e.g. 50, 100 GHz) in the transmission link of DWDM systems, so after long distance transmission, the DWDM channels may need to be demultiplexed at first then be re-multiplexed to some subgroup (e.g. 4 or 8 channels) with larger channel spacing (e.g. 400 GHz) then be launched into the transformer. After the normal dispersion fiber in the transformer, there may be an optical de-multiplexer to demultiplex the subgroup of channels or an optical passband filter to filter ASE noise. The converted optical NRZ or quasi-NRZ pulses can be converted to electrical signal at the photodetector, which may be followed by a high gain electrical amplifier and a low pass filter (e.g. Bessel filter), then detected by a decision circuit. The low pass Bessel filters have been widely used in conventional NRZ and RZ receivers, and the 3 dB bandwidths of low pass filter Δf are normally chosen as 0.5-0.8 of bit rate for both RZ and NRZ pulses (see Webb et al., US patent 6,163,394, Dec. 2000; G. P. Agrawal, *Fiber Optic Communication Systems*, John Wiley & Sons, 1997, pp. 157, 172; Bakshi et al, "Soliton interaction penalty reduction by receiver filtering", *IEEE Photon. Tech. Lett.*, Vol. 10, 1998, pp. 1042-1044.). In our receiver after the transformer, the high gain electrical amplifier and the low pass filter after are optional, and the optimum filter bandwidth should be larger than the conventional NRZ receiver also.

As an example, we experimentally demonstrated the invention to transform 10 Gbit/s conventional soliton RZ pulses to quasi-NRZ pulses. Our experiment also showed that our invention can improve the Q factor by as large as 5.4 dB compared to conventional RZ detection scheme which detects RZ pulses directly and use low pass

electrical filter to filter noise (See M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250; M. Suzuki and H. Toda, "Q-factor improvement in a jitter limited optical RZ system using nonlinearity of normal dispersion fiber placed at receiver", OFC'2001, Anaheim, paper WH3, 2001). 5.4 dB of Q improvement is a significant improvement. Although the US Pat. No. 6,448,913 B1 issued to Prucnal et al. discloses a RZ to NRZ optical pulse transformer based on TOAD, Prucnal et al's transformer degrades the system performance seriously instead of improving the performance. Their own experimental results shows that their technique has at least 7 dB of Q penalty or 12 dB of power penalty (see Fig. 5 of L. Xu, B. C. Wang, V. Baby, I. Glesk, P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter", IEEE Photonics Technol. Lett., Vol. 15, N. 2, 2003, pp. 308-310.). To our knowledge, our pulse transformer is the only transformer which can improve the system performance (i.e. Q).

In long haul systems, there are two popular techniques to improve the Q factor, where one is the forward-error-correction (FEC) technique and another is the Raman amplifier technique. Typically, the FEC technique can increase Q by about 5-8.5 dB. However, it requires about 7% or higher overhead in transmission rate and is difficult to implemented in 40 Gbit/s systems directly because of the difficulty to make high electrical bandwidth transmitters and receivers. The Raman amplifier technique can improve Q by 2-5 dB typically. Therefore, the technique in this invention is an important alternative to the FEC and the Raman amplifier techniques in long haul systems. The new technique is more powerful than the typical Raman amplifier technique and is as powerful as the FEC technique but with significantly reduced complications and without requiring the transmission overhead. Therefore, our new technique is the third technical breakthrough after FEC and Raman amplifier in long haul systems. By using this technique, all influences of the generalized timing jitter (induced from the Gordon-Haus timing jitter, PMD, cross-phase modulation, four-wave-mixing and pulse interaction etc.), the amplitude fluctuation and the ISI are reduced significantly. This invention is especially useful in 40 Gbit/s long haul and ultra-long haul systems and 10 Gbit/s ultra-

long haul systems, where the generalized timing jitter induced by PMD and cross-phase modulations are the major degrading factors. By putting a gap between neighbor converted quasi-NRZ pulses, this invention can also reduce the PMD penalty induced by the ISI from PMD induced pulse broadening. Although other PMD compensators can reduce the PMD induced timing jitter, they are complex, expensive and difficult to manufacture. At present, there are no existence of commercial available 40 Gbit/s PMD compensator. Although there are commercial available 10 Gbit/s PMD compensators, those are only for single channel, and are complex and expensive. On the contrary, this technique is very simple, and needs only one optical amplifier, normal dispersion fiber and (optional) optical filter.

In front of receivers of many existing optical fiber transmission systems, there exist normal dispersion fibers as post-dispersion compensation units (where only the linear dispersion effect was used) and the pre-amplifier EDFA with optical filters, in such cases, our invention even does not require additional components. The only modifications required are to change the pre-amplifier EDFA to a relative high power version (e.g. 15-19 dBm/channel or higher), and to relocate it to a suitable position in the post-dispersion compensation fiber unit. Then we can take advantage of the large nonlinear effect for the high power pulses to improve the system performance.

BRIEF DESCRIPTION OF THE DRAWING

Fig. 1 illustrates that when the timing jitter is larger than the half of FWHM of RZ pulses, a bit error occurs. To illustrate the ideas simply, we assume no electrical filter, and no amplitude noise.

Fig. 2 illustrates that when the timing jitter is larger than the half of FWHM of NRZ pulses, a bit error occurs. To illustrate the ideas simply, we assume no electrical filter, and no amplitude noise.

Fig. 3 illustrates one WDM transmission system which uses RZ format as the transmission format, then transforms RZ format to NRZ format, and finally uses NRZ or flat top quasi-NRZ as the detection format.

Fig. 4 illustrates a transformer receiver unit which includes a single channel optical pulse

transformer, which transforms optical RZ pulses to NRZ or quasi-NRZ pulses, and a receiver.

Fig. 5 illustrates a transformer receiver unit which includes a multiple channels optical pulse transformer, which transforms optical RZ pulses to NRZ or quasi-NRZ pulses, and receivers.

Fig. 6 illustrates one optical pulse transformer consisted of one amplifier, one (optional) band-pass filter and one span of normal dispersion fiber.

Fig. 7 illustrates one optical RZ pulse evolves flat top quasi-NRZ pulse when propagating along the normal dispersion fiber with Kerr nonlinearity.

Fig. 8 The Schematic diagram of the proposed transformer receiver unit used in our experiment. NDF stands for normal dispersion fiber.

Fig. 9 The Eye diagrams of the transmitted 10 Gbit/s solitons at 16,000 km observed (a) without electrical lowpass filter, (b) with a lowpass filter with 7.5 GHz bandwidth, and (c) with the proposed method. Horizontal axis: 25 ps/div.

Fig. 10 Measured threshold voltage and detection time of the BER detector where BER equals 10^{-7}.

Fig. 11 Measured BER at 12,000 km transmission versus the threshold voltage. The detection time was adjusted to minimize the BER for both cases.

DETAILED DESCRIPTION OF THE INVENTION

To illustrate the idea of that the NRZ format has larger generalized timing jitter tolerance than the RZ format, we first simply assume no electrical filter after the photodetector, and no amplitude noise. In this case, we can assume the decision threshold is 0.5 times of pulse peak voltage approximately. Here we take a 40 Gbit/s system as an example, we assume the bit period T_b is 25 ps for both RZ and NRZ formats as shown in Figs.1 and 2. Fig.1 shows that when the generalized timing jitter is larger than the half of FWHW pulse width of RZ pulses $T_{FWHM, RZ}$, the voltage at the decision instant (i.e., 0 ps) will be less than the decision threshold 0.5, then there is a bit error. Where the solid curve 11 is the average RZ pulse whose peak is located at 0 ps, and the dashed curve 12 is the instantaneous pulse whose peak shifts to the half of $T_{FWHM, RZ}$ because of the generalized timing jitter induced by the Gordon-Haus timing jitter, PMD, cross-phase

modulation, four-wave-mixing or pulse interaction etc. Fig. 2 shows that if the generalized timing jitter is larger than the half of FWHW pulse width of NRZ pulses $T_{FWHM, NRZ}$, there is a bit error. Where the solid curve 21 is the average NRZ pulse whose peak is located at 0 ps, and the dashed curve 22 is the instantaneous pulse whose peak shifts to the half of $T_{FWHM, NRZ}$=25 ps because of the generalized timing jitter. To avoid ISI penalty, $T_{FWHM, RZ}$ should be chosen to be less than the bit period T_b i.e. $T_{FWHM, NRZ}$, therefore the NRZ format has larger generalized timing jitter tolerance than the RZ format.

When a low pass electrical filter is put after the photodetector, RZ pulses can broaden. Even in this case, the broadened FWHM pulse width $T_{FWHM, RZ}$ still should be less than the bit period (i.e., the FWHM pulse width of NRZ pulses without filter) to avoid too large ISI penalty. Therefore, in this case, NRZ format still has larger generalized timing jitter tolerance than the RZ format.

It is noted that the NRZ pulses may not strictly be the rectangular pulses both in optical domain (before the photodetector) and the electrical domain (after the photodetector), the electrical NRZ pulses (after the photodetector) are normally with the leading edge and trailing edge because of the limited response time of the photodetector.. Although NRZ format is good format at receiver to reduce the influence from the generalized timing jitters, the ISI may be large in some systems. Especially in systems without too large timing jitter, it will be helpful to use the quasi-NRZ format instead of the strict NRZ format, where the quasi-NRZ pulses are with flat top (i.e. rectangular) shape and there are gaps between neighbor pulses and the duty ratio can be in a range of 1:3 to 1:1 instead of 1:1 for strict NRZ pulses. In our invention, the optical pulse transformer can convert non-flat-top bell shape RZ pulses to either strict NRZ or quasi-NRZ pulses. The gap between the flat-top quasi-NRZ pulses can act a guard band to avoid the ISI induced from PMD which tends to broaden the pulses, in this case, our pulse transformer also acts as a PMD compensator.

In high speed (10 Gbit/s, 40 Gbit/s and higher) long haul systems (especially in long haul ultralong haul undersea and terrestrial systems), RZ formats (including dispersion managed soliton, CRZ, conventional soliton, non-chirped RZ, carrier-suppressed RZ, carrier-suppressed CRZ and DPSK etc.) have been widely used in

practical systems, because RZ formats normally have better transmission performance than NRZ format. The pulse shapes in all of these RZ systems are non-flat-top bell shapes.

In this invention, we use RZ format as the transmission format because of their good transmission performance, then we transform the RZ formats to NRZ or flat top quasi-NRZ format by using the high nonlinear effect in a normal dispersion fiber for very high power pulses, finally we use the NRZ or quasi -NRZ format as the detection format. Where we call the device, which transforms the optical RZ pulses to optical NRZ or quasi-NRZ pulses, as an optical pulse transformer. In this invention, the meaning of using a RZ format as the transmission format is that the transmitter generates optical non-flat-top RZ pulses, the optical RZ pulses may keep RZ pulse shapes or may become complex pulse shapes (non-RZ-like shapes) in the (optional) pre-compensation-unit, transmission link and the (optional) post-dispersion unit, at the end of the transmission link or the (optional) post- compensation-unit, the optical pulses return back to the RZ format.

Fig. 3 illustrates one WDM transmission system using the present invention, there the each transmitter 31, which normally includes a laser diode, intensity modulator, data modulator and (optional) phase modulator etc. (or which may be a direct modulated laser diode), generates a train of optical RZ pulses with individual wavelength channel, then the WDM multiplexer (or fiber coupler) 32 combines optical RZ pulses of multiple wavelength channels to the same fiber. The optical RZ pulses may pass through a pre-dispersion compensation unit 33, which is optional, then they enter into the optical amplifier 34 of the transmission link. The pre-dispersion compensation unit 33 is used to compensate the dispersion of transmission link. The pre-dispersion compensation unit can be put after WDM multiplexer 32 to compensate the dispersion of multiple channels simultaneously, and it can also be put before the WDM multiplexer 32 to compensate the dispersion of the individual channel separately. The optical RZ pulses may become complex shapes after pre-dispersion compensation unit 33, and they can also evolve to complex pulse shape in the transmission link. (Under these circumstances, we still call it to use RZ format as the transmission format following the normal terminology). If there is no pre-dispersion compensation unit 33, the optical RZ pulses directly enter into the optical amplifier 34 of the transmission link. Optical pulses transmit over the

transmission link consisted of fiber spans and optical amplifiers 34. After the transmission link, optical pulses pass through the first post-dispersion compensation unit 35, which is optional, to compensate the dispersion of multiple channels simultaneously. After the first post-dispersion compensation unit 35, the total channels are demultiplexed by the WDM demultiplexer (or couplers with filters) 36 to individual channels or sub-group of channels. The second post-dispersion unit 37, which is optional, compensates the dispersion of individual channels or sub-group of channels. Finally, in the transformer receiver unit 38 of the invention, the optical RZ pulses of individual channel or of sub-group of channels are transformed into NRZ pulses and detected by the receiver.

Fig. 4 shows the detail configuration of this novel transformer receiver unit 38 (of Fig. 3) for single channel, which includes the optical pulse transformer 41 and the receiver 47. Where the receiver 47 includes an (optional) optical band-pass filter 42, a photodetector 43, an (optional) high gain amplifier 44 (e.g., trans-impedance amplifier), an (optional) low pass Bessel-Thompson filter 45, and the decision circuit 46. Where the optical pulse transformer 41 transforms optical RZ pulses to NRZ or quasi-NRZ pulses, which pass through the (optional) optical bandpass filter 42 later to filter ASE noise generated by optical amplifiers. The filtered NRZ or quasi-NRZ optical pulses are converted to the electrical NRZ pulses by the photodetector 43, and then the electrical NRZ or quasi-NRZ pulses are amplified by the high gain amplifier 44. Then the amplified NRZ or quasi-NRZ pulses pass through the low pass Bessel-Thompson filter 45, which is optional. Even there is the low pass Bessel-Thompson filter 45, its optimal bandwidth for NRZ pulses in our invention is normally different from that for RZ pulses in conventional receivers. Finally the electrical pulses are detected by the decision circuit 46.

In some high speed systems (e.g., 40 Gbit/s per channel), there are two sub-channels (e.g. 20 Gbit/s per sub-channel) with orthogonal polarizations for one wavelength channel, and this kind of system is often called as the optical-time-division-multiplexing (OTDM) system. At the receiver, there is an optical polarization beam splitter (PBS) to split the one wavelength channel (e.g. 40 Gbit/s) to two sub-channels (e.g., 20 Gbit/s). In this OTDM system, our optical pulse transformer can be put either after the PBS to transform the two sub-channels (e.g., 20 Gbit/s) separately or before the

PBS to transform one wavelength channel (e.g., 40 Gbit/s) wholly.

Fig. 5 shows the detail configuration of the present novel transformer receiver unit 38 (of Fig. 3) for a sub-group of channels, which includes the optical pulse transformer 50, the WDM demultiplexer 51 (or couplers with filter), the (optional) post-dispersion compensation-unit 52 and the receiver 58. The main difference between Fig. 4 and Fig. 5 is that the pulse transformer 41 only transforms optical RZ pulses of single channel to optical NRZ or quasi-NRZ pulses, but the common pulse transformer 50 transforms optical RZ pulses of a sub-group of channels to optical NRZ or quasi-NRZ pulses. Although the channel spacing of the WDM demultiplexer 51 can be the same as the channel spacing in transmission link, to reduce the potential cross talks in the optical pulse transformer 50 and to reduce the cost, it is better to choose its channel spacing several times (e.g. 4 or 8 times) larger than the channel spacing in transmission link. After the optical NRZ or quasi-NRZ pulses are demultiplexed by the WDM demultiplexer 51 (or coupler with filter), they pass through the (optional) post-dispersion compensation-unit 52, which compensates the dispersion of individual channel. After that, the optical RZ pulses pass through an (optional) optical bandpass filter 53 to filter ASE noise generated by optical amplifiers. The filtered optical NRZ or quasi-NRZ pulses are converted to the electrical NRZ or quasi-NRZ pulses by photodetector 54, and then the electrical NRZ or quasi-NRZ pulses are amplified by a high gain amplifier 55 (e.g., trans-impedance amplifier). Then the amplified NRZ or quasi-NRZ pulses pass through a low pass Bessel-Thompson filter 56, which is optional. Even with the low pass Bessel-Thompson filter 56, its optimal bandwidth for NRZ or quasi-NRZ pulses in the present invention is normally different from that for RZ pulses in conventional receivers. Finally the electrical pulses are detected by the decision circuit 57. In comparison to the configuration of Fig.4, the configuration of Fig. 5 is less costly because of fewer optical pulse transformers.

Although Fig. 3-5 only shows the point to point WDM transmission systems, the present invention can be used in mesh networks and/or ring networks as well. In mesh and ring networks, there may be optical switches, optical channel add-drop multiplexers, optical cross-connect, and routers etc. What we need to do is just to insert an optical pulse

transformer in front of photodetector to transform optical RZ pulses to NRZ or quasi-NRZ pulses.

The invention is suitable for WDM, DWDM systems and single channel systems.

The invention can be used in both undersea and terrestrial systems, and it is especially useful in long haul and ultra long haul high speed (e.g., 10 Gbit/s per channel, 40 Gbit/s per channel and higher) systems.

Fig. 6 shows the detail configuration of an optical pulse transformer which consists of a pre-amplifier 60, an (optional) optical filter 61 and a span of normal dispersion fiber 62 (See M. Suzuki, H. Toda, A. Liang, & A. Hasegawa "Experimental Verification of Improvement of a phase margin in optical RZ receiver using Kerr nonlinearity in normal dispersion fibers," ECOC'00, Munich, Germany, vol. 4, pp. 49-50, 2000.). Here the optical pre-amplifier 60, which can be an EDFA, Raman or semiconductor amplifier, amplifies an optical RZ pulse to a relative high power level, the (optional) optical filter 61 filters the ASE noise from the optical amplifier. When the high power RZ optical pulse propagates along normal dispersion fiber 61, its temporal waveform changes to a NRZ-like pulse by the effects of group velocity dispersion and Kerr nonlinearity (See G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, pp. 106-111, 1995). The configuration of Fig. 6 can transform not only single channel RZ pulses to NRZ or to quasi-NRZ pulses, but also multiple channels (e.g. 4 or 8) RZ pulses to multiple channels NRZ or quasi-NRZ pulses simultaneously (where the channel spacing should be large enough to reduce the cross talks between different channels, e.g., we can do this by picking up one channel from every four or eight channels.). In this case, we do not need one preamplifier and one span (e.g. several tens of km) of normal dispersion fibers for each channel, we can share the same preamplifier and the same span of normal dispersion fibers for multiple wavelength channels and it will reduce the cost and complexity of systems significantly.

Fig. 7 shows one optical RZ pulse evolves flat-top quasi-NRZ pulse when propagating along the normal dispersion fiber with Kerr nonlinearity. Where the normalized time=t/t_0, the normalized distance=z/z_0, and the normalized power $N(t)=p(t)/P_0$, with t the time, z the distance, $p(t)$ the intensity profile, and $t_0 = T_{FWHM}/1.76$,

$z_0 = 0.322\frac{\pi^2 c^2 T_{FWHM}^2}{|D|\lambda}$, $P_0 = \frac{nc\lambda A_{eff}}{16\pi z_0 n_2}\times 10^{-7}$ and T_{FWHM} the FWHM pulse width of the RZ pulse, c the light speed, D the dispersion of fiber, λ the wavelength, n the refractive index of fiber, n_2 the nonlinear-index coefficient, and A_{eff} the effective core area. When the normalized power is large, it will induce frequency chirp imposed on the pulse because of the strong self-phase modulation. In the case of normal dispersion, the pulse becomes flat top quasi-NRZ (or rectangular) pulse with relatively sharp leading and trailing edges and is accompanied by a linear chirp across its entire width. Not only the pulse shape changes to the flat top quasi-NRZ format (or rectangular shape), but also the optical spectrum are broadened seriously.

Fig. 8 shows the schematic diagram in our experiment for the proposed transformer receiver unit, which is constructed by an EDFA with about 15-19 dBm of output power, an optical band-pass filter (OBPF) which reduces the ASE, a span (about 20 km) of normal dispersion fiber (NDF), a photodetector (PD) and a decision device. The launched RZ pulses power (15-19 dBm) is equivalent to as high as 10-13th of soliton order in a fiber with -3 ps/km/nm of normal dispersion. The launched power and NDF length are optimized by the results of numerical simulation. In some RZ transmission systems with anomalous residual dispersion (e.g., in conventional soliton) , the normal dispersion of this NDF will have extra favorite effects in reducing the Gordon-Haus timing jitter accumulated in the transmission fiber with anomalous dispersion. However, the linear dispersion effect in our pulse transformer only plays very little role to compensate the total residual dispersion of the transmission link, and the nonlinear effect plays major role in reducing the influences of timing jitters and amplitude jitter. For example, in our experiment for the 10 Gbit/s soliton transmission, the dispersion and length for transmission fibers are 0.88 ps/km/nm and 12,000 km respectively, and the dispersion and length for the normal dispersion fiber in the transformer are -3 ps/km/nm and 20 km respectively (See M. Suzuki, H. Toda, A. Liang, & A. Hasegawa "Experimental Verification of Improvement of a phase margin in optical RZ receiver using Kerr nonlinearity in normal dispersion fibers," ECOC'00, Munich, Germany, vol. 4, pp. 49-50, 2000.). The normal dispersion fiber in the transformer only reduces the total residual dispersion by about 0.6% (i..e. 60 over 10560 ps/nm). In the receivers of many

transmission systems, there are already preamplifier EDFA in front of the photodetector and the normal dispersion fiber as the post-dispersion compensation unit, so it is very easy to change these existing systems to this proposed transformer receiver unit by simply increasing the output power of EDFA and moving it to the right position in the normal dispersion fiber of the post-dispersion compensation unit.

We have carried out 10 Gbit/s soliton transmission experiment in a sliding frequency recirculating loop in order to compare the characteristics of the proposed method and the conventional RZ optical receiver. When the pulses are detected with the conventional scheme, the EDFA and NDF are removed and the electrical lowpass filter is inserted after the photodiode. Fig. 9 shows the eye diagrams of the transmitted pulses at 16,000 km observed (a) without electrical low-pass filter, (b) with a low-pass filter with 7.5 GHz bandwidth, (which is typically used in present 10 Gbit/s systems) and (c) with the proposed method, respectively. The electrical bandwidth of the photodiode (PD) and the sampling oscilloscope are 32 and 50 GHz, respectively. The average optical power to the PD and the vertical scale of the sampling oscilloscope are kept equal for all the measurements. We can see in Fig. 9 (b) that the pulse is broadened by the low pass filter. However, the amplitude jitter on "0" signals was increased because of the ISI. As shown in Fig. 9 (c), the waveform of the RZ pulses are changed to a flat-top quasi-NRZ format by utilizing normal dispersion and self-phase modulation in the NDF, while the amplitude of the pulses is nearly the same with in the case of Fig. 9 (b). The eye opening is wider than that detected with the 7.5-GHz low pass filter. The amplitude fluctuations at the center portion of converted flat-top quasi-NRZ pulses are pretty small and are even smaller than the original amplitude fluctuations, which mainly comes from the pulse interactions and ASE noise, of transmitted RZ pulses, we call this phenomena as the nonlinearity clamping which happens in normal dispersion region for pulses with a large power and can be thought as a counterpart of modulation instability in anomalous dispersion region. In addition, the amplitude jitters at the center portion of "0" signals are remarkably small, because there is not an electric low pass filter which can reduce ISI. Next, we measured the threshold voltage and the detection time of the BER detector where BER equals 10^{-7}. We optimized the state of polarization for all the measurements with the polarization controller (PC) in the loop. Fig. 10 shows the result. The obtained

amplitude margin detected with the proposed method was 100 mV, which was 70% larger than that with the conventional method. The improvement of the phase margin is about 18%. Fig. 11 shows the measured BER versus the threshold voltage of the BER detector at 12,000 km transmission. In this case, we adjusted the detection time to minimize the BER for all the measurements. The averaged optical power to the PD is different from the case of Fig. 10. When the transmitted pulses are detected with the 7.5-GHz low pass filter, the amplitude margin at the BER of 10^{-9} is 19.3 mV. On the contrary, when the transmitted pulses are detected with the proposed method, the margin is 56.0 mV, which is about 3 times larger than that of the conventional RZ receiver using the 7.5-GHz low pass filter. The measurement values of Q factor are 17.8 dB for the low pass filter and 23.2 dB for the present invention respectively (See M. Suzuki, H. Toda, A. Liang, & A. Hasegawa, "Improvement of Amplitude and Phase Margins in an RZ Optical Receiver using Kerr Nonlinearity in Normal Dispersion Fiber", IEEE Photonics Technol. Lett., Vol. 13, 2001, pp. 1248-1250; M. Suzuki and H. Toda, "Q-factor improvement in a jitter limited optical RZ system using nonlinearity of normal dispersion fiber placed at receiver", OFC'2001, Anaheim, paper WH3, 2001). Therefore, the present invention can increase Q by as large as 5.4 dB, which is a very significant improvement on system performance. In practical systems, even 1 dB of Q improvement has been considered to be significant. To our knowledge, only the forward-error correction and the Raman amplifier techniques can increase Q by more than 5 dB. By optimizing the transformer and receiver further, we may improve the Q factor further.

Although we demonstrated the EDFA as the preamplifier to transform the RZ pulses to NRZ pulses, both distributed, discrete Raman amplifiers and semiconductor amplifiers can be used as the same purpose. In these cases, the distributed Raman amplifier pump unit can be put after the NDF, and the discrete Raman amplifier can be put either after or/and before the NDF.

When there is frequency chirping for the optical RZ pulses after the transmission link or after the post dispersion compensation unit, we still can use the configuration of Fig. 6 to transfer optical RZ pulses to optical NRZ or quasi-NRZ pulses.

The invention is useful for noise-limited and/or generalized timing jitter-limited systems, and dispersion-managed systems and/or non- dispersion-managed systems.

The present invention is not limited to the above-described embodiments. Numerous modifications and variations of the present invention are possible in light of the sprit of the present invention, and they are not excluded from the scope of the present invention. Accordingly, many modifications may be made by one of ordinary skill in the art without departing from the spirit and scope of the appended claims.

I/We claim:

1. A method to improve the system performance-Q factor of a high speed optical fiber transmission system by

   generating a RZ format at a transmitter,

   transmitting said RZ format over a dispersion managed optical transmission medium,

   transferring said RZ format to a NRZ or quasi-NRZ format in front of a receiver by an optical pulse transformer which takes advantage of high nonlinear Kerr effect in normal dispersion fiber for pulses with a power such that dispersion length is at least two times larger than nonlinear length,

   then detecting said NRZ or quasi-NRZ format at said receiver.

2. The invention defined in claim 1 wherein said optical pulse transformer consists of an optical amplifier, a normal dispersion fiber, and some accessories such that

   an optical filter between said optical amplifier and said normal dispersion fiber,

   an optical filter after said normal dispersion fiber,

   an optical demultiplexer after said normal dispersion fiber,

   an optical attenuator after said normal dispersion fiber.

3. The invention defined in claim 1 wherein said optical pulse transformer can improve the Q factor by increasing tolerances of both amplitude fluctuation and generalized timing jitter.

4. The invention defined in claim 1 wherein said optical pulse transformer can act as a polarization-mode-dispersion (PMD) compensator to compensate the PMD penalty induced from ISI.

5. The invention defined in claim 1 wherein said RZ format can be but not limited to be a format of dispersion managed soliton, conventional soliton, chirped-RZ, non-chirped RZ, carrier-suppressed RZ, carrier-suppressed chirped-RZ, and differential-phase-shift-keys RZ etc.

6. The invention defined in claim 1 wherein said dispersion managed optical transmission medium includes transmission fibers, inline dispersion compensation units, optical amplifiers, and other units such as a pre-dispersion compensation unit in or after said transmitter and a post-dispersion compensation unit before said optical pulse transformer.
7. The invention defined in claim 1 can be used to install a new system, or to upgrade an existing system by adding more channels, or to replace some degraded channels.
8. The invention defined in claim 1 wherein said quasi-NRZ format is a flat top pulse with a duty ratio of 1:3 to 1:1.
9. An high speed optical fiber transmission system comprising at least an optical transmitter to generate optical RZ pulses, WDM multiplexers or couplers, a dispersion managed optical transmission medium, WDM demultiplexer or optical filters, an optical pulse transformer, which transfers said optical RZ pulses to optical NRZ or quasi-NRZ pulses, by using high nonlinear Kerr effect in normal dispersion fiber for pulses with a power **such that dispersion length is at least two times larger than nonlinear length**, and a receiver to detect said optical NRZ or quasi-NRZ pulses.
10. The invention defined in claim 9 wherein said optical RZ pulses can be but not limited to be the format of dispersion managed soliton, conventional soliton, chirped-RZ, non-chirped RZ, carrier-suppressed RZ, carrier-suppressed chirped-RZ, and differential-phase-shift-keys RZ etc.
11. The invention defined in claim 9 wherein said optical RZ pulses of each wavelength channel can have either two orthogonal polarization sub-channels or two co-polarization sub-channels at same wavelength.
12. The invention defined in claim 9 wherein said dispersion managed optical transmission medium includes transmission fibers, inline dispersion compensation fibers, optical amplifiers and possible other units such as a pre-dispersion compensation unit in or after said transmitter and a post-dispersion compensation unit before said optical pulse transformer.

13. The invention defined in claim 9 wherein said optical fiber transmission system can be a noise limited system or/and a generalized timing-jitter limited systems.
14. The invention defined in claim 9 wherein said optical fiber transmission system can be a point to point network, ring network or mesh network in a terrestrials or undersea system.
15. The invention defined in claim 9 wherein said optical fiber transmission system can be a WDM system or single-wavelength system.
16. The invention defined in claim 9 wherein said optical pulse transformer can transform said optical RZ pulses of either single wavelength channel or multiple wavelength channels to said NRZ or quasi-NRZ pulses.
17. The invention defined in claim 9 wherein said optical RZ pulses in front of said optical pulse transformers can be either with or without frequency chirp.
18. The invention defined in claim 9 wherein said receiver includes at least a photodetector and a decision circuit and possible some accessories such that an optical filter, a high-gain electrical amplifier, and a low pass electrical filter etc..
19. The invention defined in claim 9 wherein said optical pulse transformer consists of an optical amplifier, a normal dispersion fiber, and some accessories such that

an optical filter between said optical amplifier and said normal dispersion fiber,

an optical filter after said normal dispersion fiber,

an optical demultiplexer after said normal dispersion fiber,

an optical attenuator after said normal dispersion fiber.

20. An high speed optical soliton transmission system comprising

    at least an optical soliton transmitter to generate optical RZ pulses, WDM multiplexers or couplers, an optical transmission medium with anomalous dispersion, WDM demultiplexer or optical filters, an optical pulse transformer, which transfers said optical RZ pulses to optical NRZ or quasi-NRZ pulses, by using high nonlinear Kerr effect in normal dispersion fiber for pulses with a power **such that dispersion length is at least two times larger**

than nonlinear length, and a receiver to detect said optical NRZ or quasi-NRZ pulses.

ABSTRTACT

An optical pulse transformer, which consists of an optical amplifier and a normal dispersion fiber, is proposed to transform transmitted optical RZ pulses to NRZ or quasi-NRZ pulses for the purpose of improving the system performance i.e. the Q factor. A high speed optical fiber transmission system uses the RZ format as the transmission format, and uses the optical pulse transformer to transform the optical RZ format to NRZ or quasi-NRZ format in front of the receiver, then uses the NRZ format as the detection format at the receiver. In the proposed optical pulse transformer, the high Kerr nonlinear effect for the high power pulses in the normal dispersion fiber is used to increase the tolerances of both the generalized timing jitter and amplitude jitter. The experiment demonstrates that the Q factor is increased by as much as 5.4 dB, which is a significant improvement on system performance.

Drawings

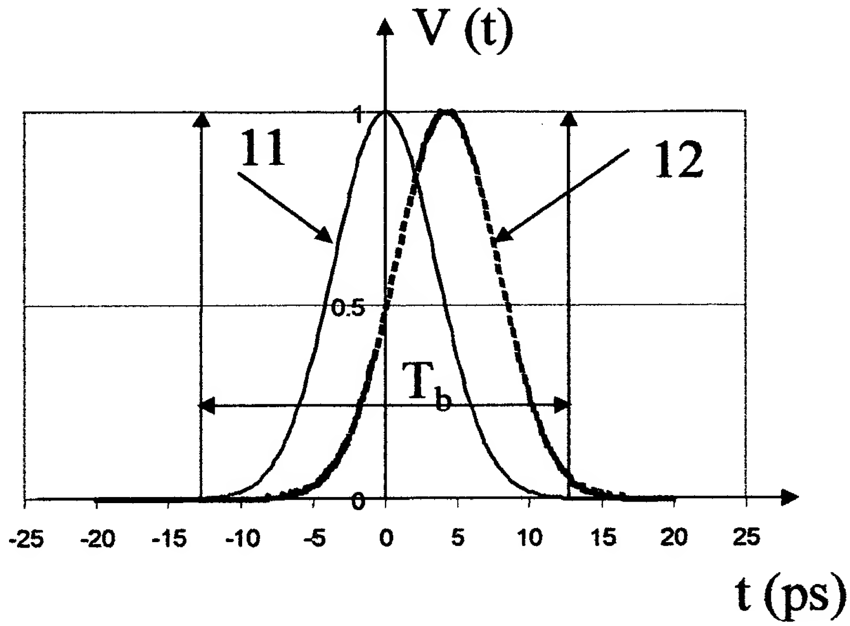


Fig. 1

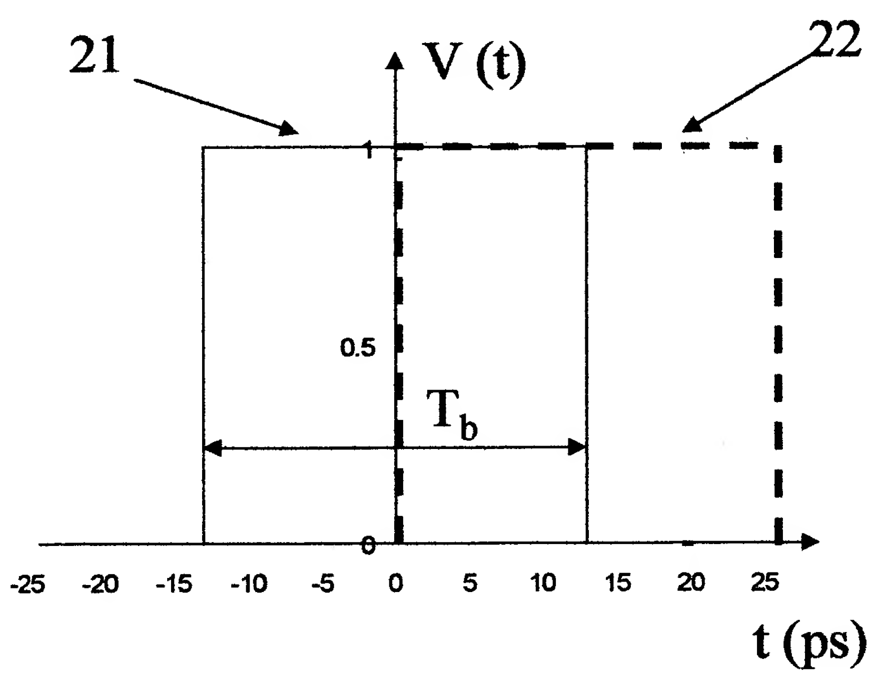


Fig. 2

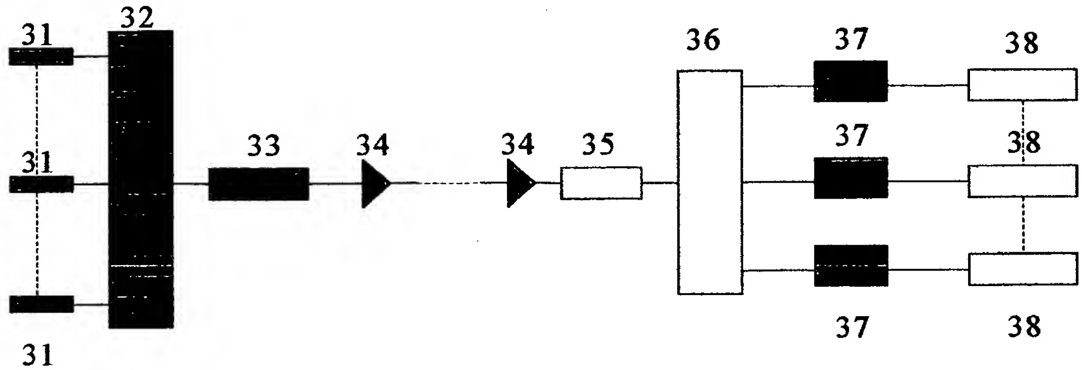


Fig. 3

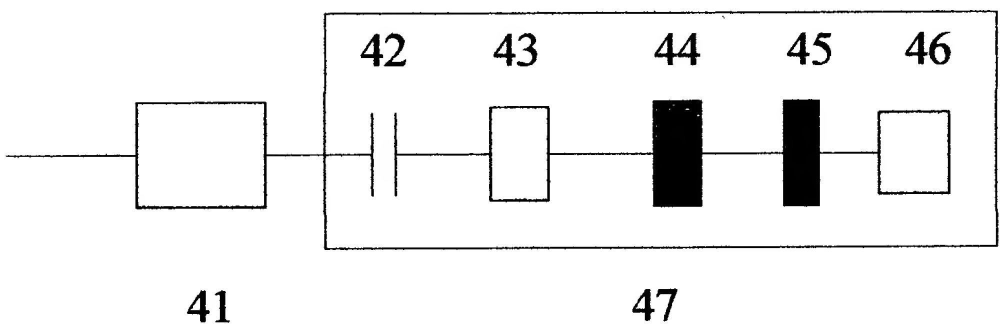


Fig. 4

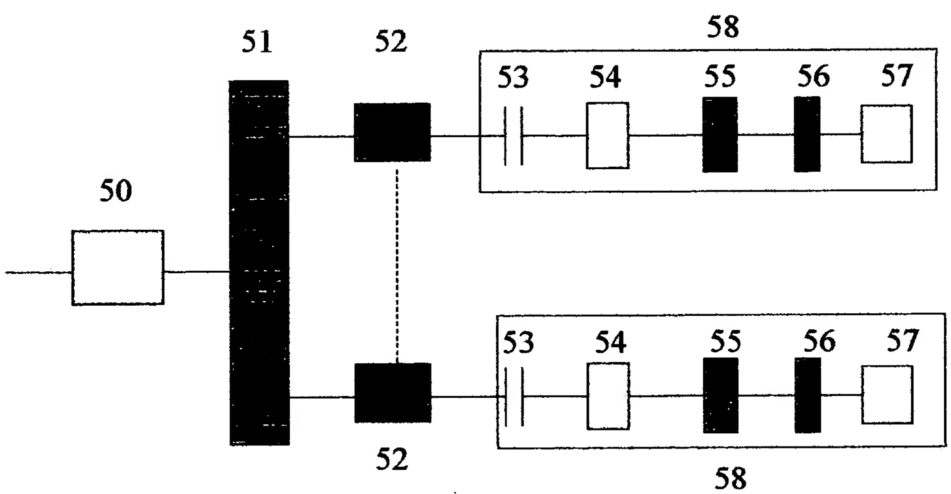


Fig. 5

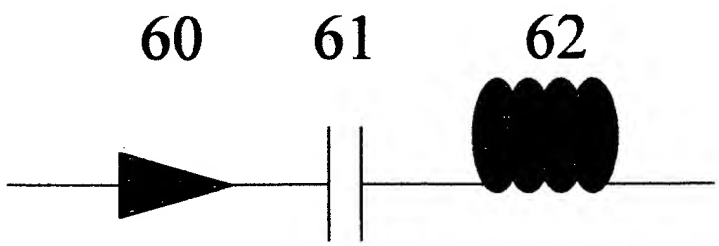


Fig. 6

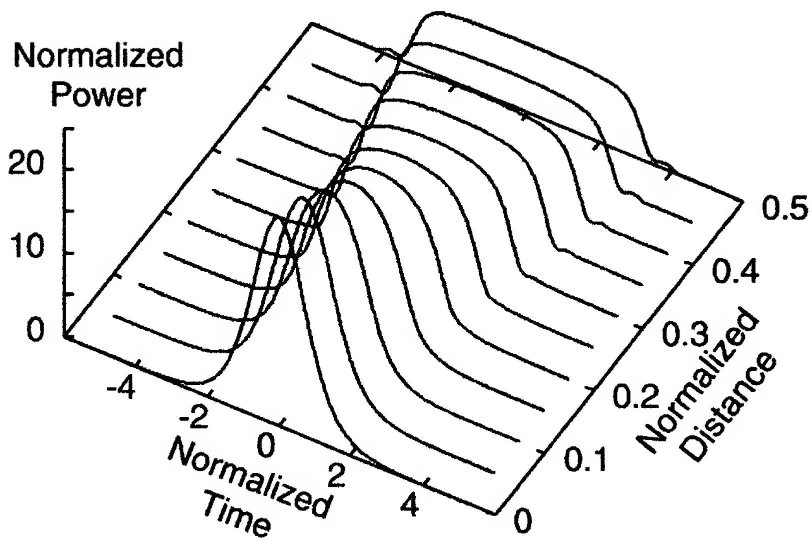


Fig. 7

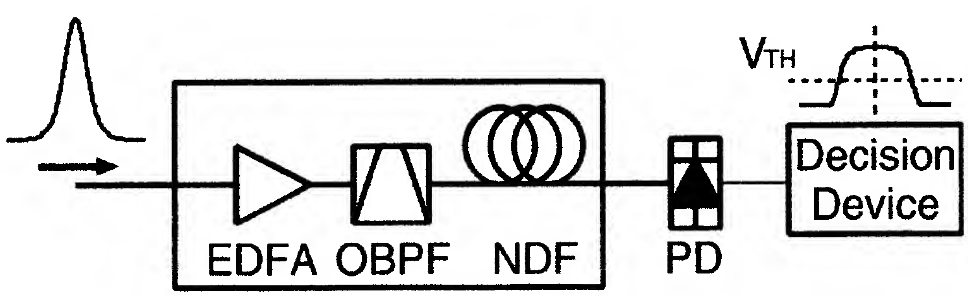
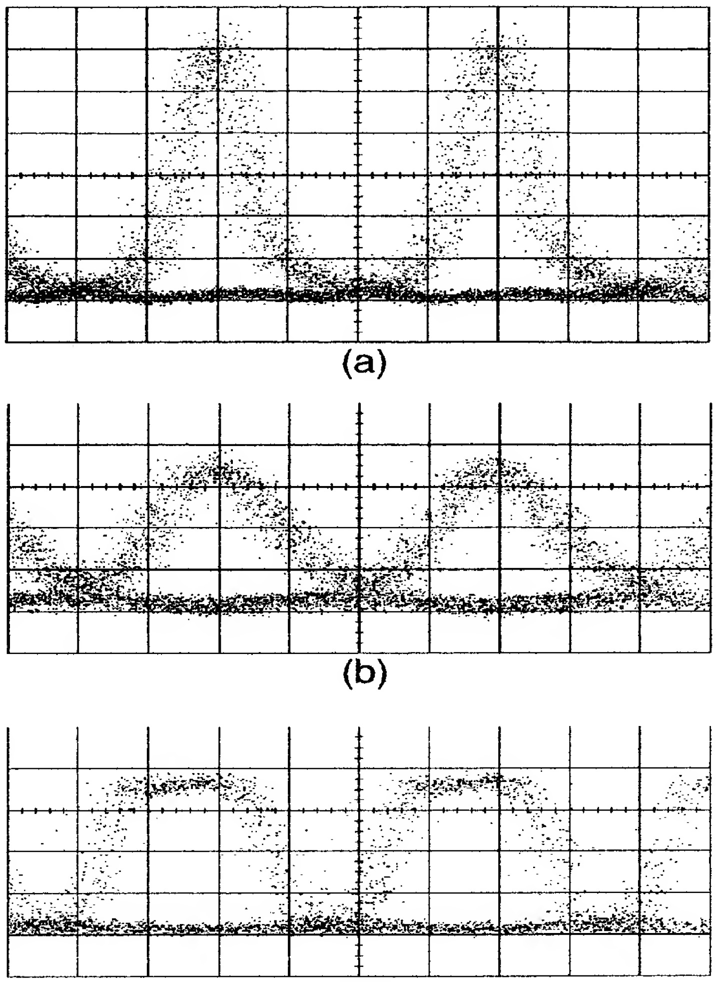


Fig. 8

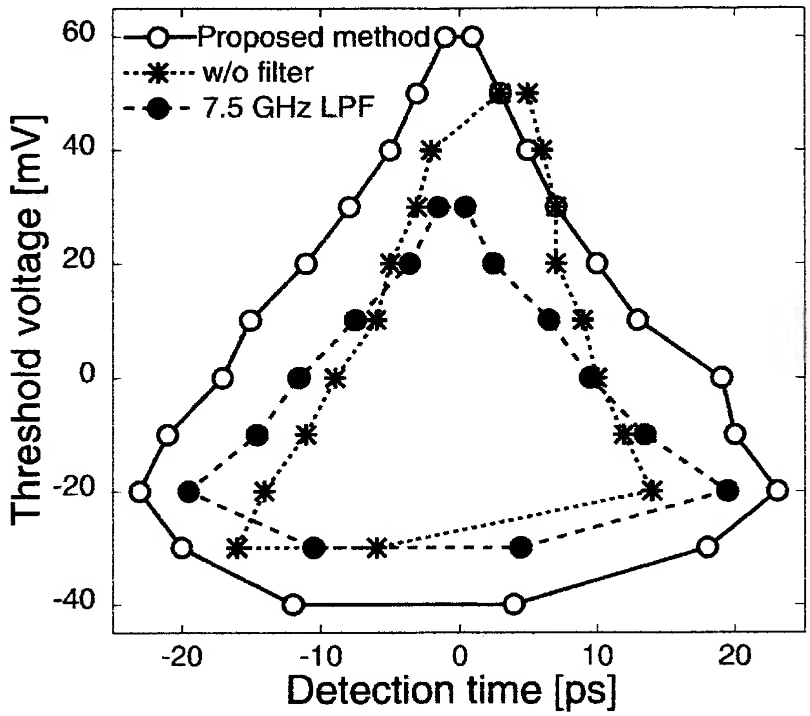


(a)

(b)

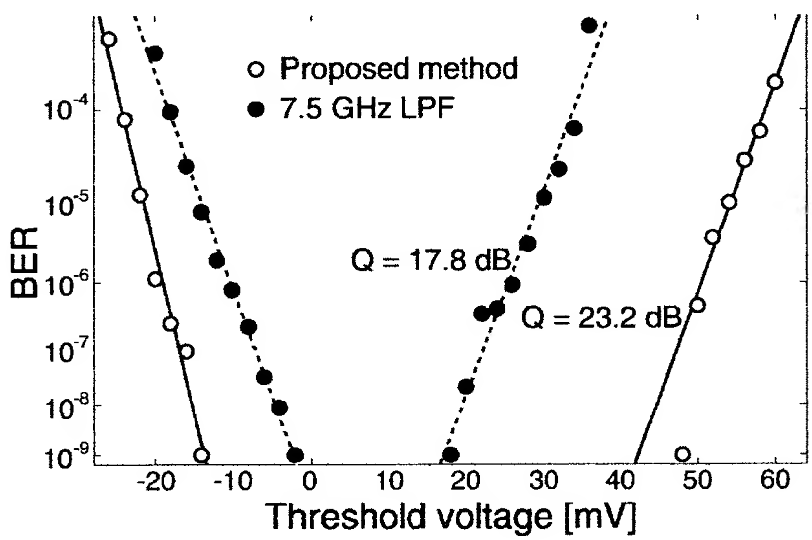
(c)

Fig. 9



Proposed method
w/o filter
7.5 GHz LPF
Threshold voltage [mV]
Detection time [ps]
60
40
20
0
-20
-40
-20
-10
0
10
20

Fig. 10



Proposed method
7.5 GHz LPF
Q = 17.8 dB
Q = 23.2 dB
BER
Threshold voltage [mV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-20
-10
0
10
20
30
40
50
60

Fig. 11